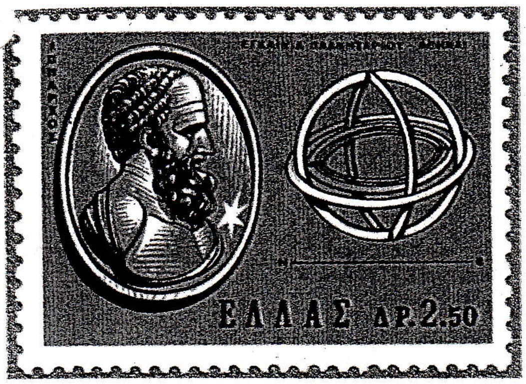


Figure 2-5 Hipparchus (2nd century BC) was the first great observational astronomer. Among other things, he constructed a catalog listing 1080 of the brightest stars by position and dividing them into six brightness classes now known as magnitudes. He is honored here on a Greek stamp, which also shows one of his observing instruments.

to the brightness of stars, and for that we must consult one of the first great astronomers.

The Brightness of Stars Hipparchus (Figure 2-5), a Greek astronomer (160–127 BC), divided the stars into six classes. The brightest were first-class stars, and those slightly fainter were second-class stars. Continuing down to the faintest stars he could see, the sixth-class stars, he recorded his classifications in a great star catalog that became a classic reference in ancient astronomy. His method, slightly modified, is still in use today as the **magnitude scale,** the astronomer's brightness scale.

Despite its value, the magnitude scale can seem confusing. First, the fainter the star, the larger the magnitude number. For instance, 6th-magnitude stars are fainter than 1st-magnitude stars. This may seem backward at first, but think of it as Hipparchus did. The brightest stars are first-class stars, and the fainter stars are second- and third-class, and so on.

Another source of confusion is that the magnitude system is not linear—that is, a change of 2 magnitudes is not twice as big as a change of 1 magnitude. We must use logarithms to describe the magnitude system because Hipparchus designed it to represent the way stars look to our eyes, and our eyes work logarithmically. If they did not, we might be able to see subtle differences in brightness by sunlight but would be totally blind in the shade. Box 2-1 (p. 28) discusses the mathematics of magnitudes.

Modern astronomers have made a major improvement in Hipparchus's magnitude system by measuring stellar brightness with sensitive instruments. For example, instead of merely saying that θ (theta) Leonis is a 3rd-magnitude star, they can say specifically that its magnitude is 3.34.

If we measured the brightness of all of the stars in Hipparchus's first brightness class, some would be brighter than 1.0. For instance, Vega (α Lyrae) is so bright that its magnitude is almost zero at 0.04. A few stars are so bright that the magnitude scale must extend past zero into negative numbers (Figure 2-6). On this scale, Sirius appears as the brightest star in the night sky with a magnitude of −1.42.

The magnitude scale is open-ended. We can extend it far into negative numbers to include the moon at about −12.5 and the sun at about −26.5. We can also extend it to objects fainter than the faintest stars we can see with the naked eye. The 5-m (200-inch) telescope can detect stars as faint as 24th magnitude.

These are known as **apparent visual magnitudes** (m_v). Such magnitudes refer to how bright the stars look and does not compensate for their distance from earth. A star that is a million times more luminous than the sun might appear very faint if it were very far away, and a star that is much less luminous than the sun might look bright if it were nearby. Look at the brightness and distance of the stars in Figure 2-2. In Chapter 9 we will develop a magnitude scale that takes distance into account and tells us how bright the stars really are. Apparent visual magnitude only tells us how bright they appear.

So far we have discussed the sky as if it were static and unchanging. Now that we are familiar with constellations, star names, and magnitudes, we can look at the sky as a whole and note its motion.

2-2 THE CELESTIAL SPHERE

A Model of the Sky Many ancient astronomers, including Hipparchus, thought of the sky as a great, hollow, crystalline sphere surrounding the earth. The stars, they imagined, were attached to the inside of the sphere like thumbtacks stuck in the ceiling. The sphere rotated once

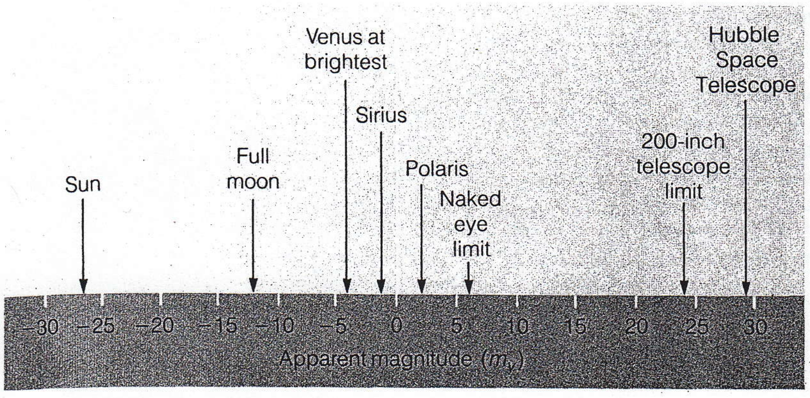


Figure 2-6 The scale of apparent visual magnitudes extends into negative numbers to represent the brighter objects.

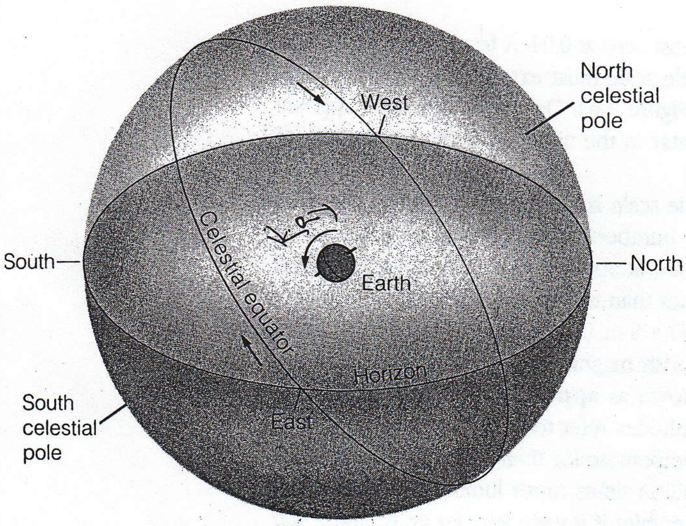


Figure 2-7 The modern celestial sphere models the appearance of the sky. The poles mark the pivots, and the equator divides the sky in half. Those objects below our horizon are invisible. The earth rotates eastward, making objects in the sky appear to rise along the eastern horizon and set along the western horizon.

a day, carrying the sun, moon, planets, and stars from east to west.

We know now that the sky is not a great, hollow, crystalline sphere. The stars are scattered throughout space at different distances, and it isn't the sky that rotates once a day—the earth turns on its axis. Although we know that the crystalline sphere is not real, it is convenient as a model of the sky and is used daily by modern astronomers when they think about the locations and motions of celestial bodies.

Our model of the sky is called the **celestial sphere,** an imaginary sphere of a very large radius surrounding the earth and to which the stars, planets, sun, and moon seem to be attached (Figure 2-7). This sphere must have a large radius so that no part of the earth is significantly closer to a given star than any other part. Then it does not matter where on the earth we go: The sky always looks like a great sphere centered on our location.

If we watch the late afternoon sky for a few hours, we can notice movement. As the rotation of the earth carries us eastward, the sun appears to move westward and eventually sets. As darkness falls, we can see the stars, and in an hour or so it becomes obvious that the eastward rotation of the earth is making the sky appear to rotate westward (Figure 2-8). As some constellations set in the west, others rise in the east.

This daily rotation of the sky is called its **diurnal motion.** The word *diurnal* means daily. The diurnal motion of the sky is only an illusion produced by the daily rotation of the earth on its axis.

Reference Marks on the Sky The pivots about which the sky seems to rotate are called the celestial poles. The **north celestial pole** is the point on the sky directly above the earth's North Pole, and the **south celestial pole** is the point directly above the earth's South Pole.

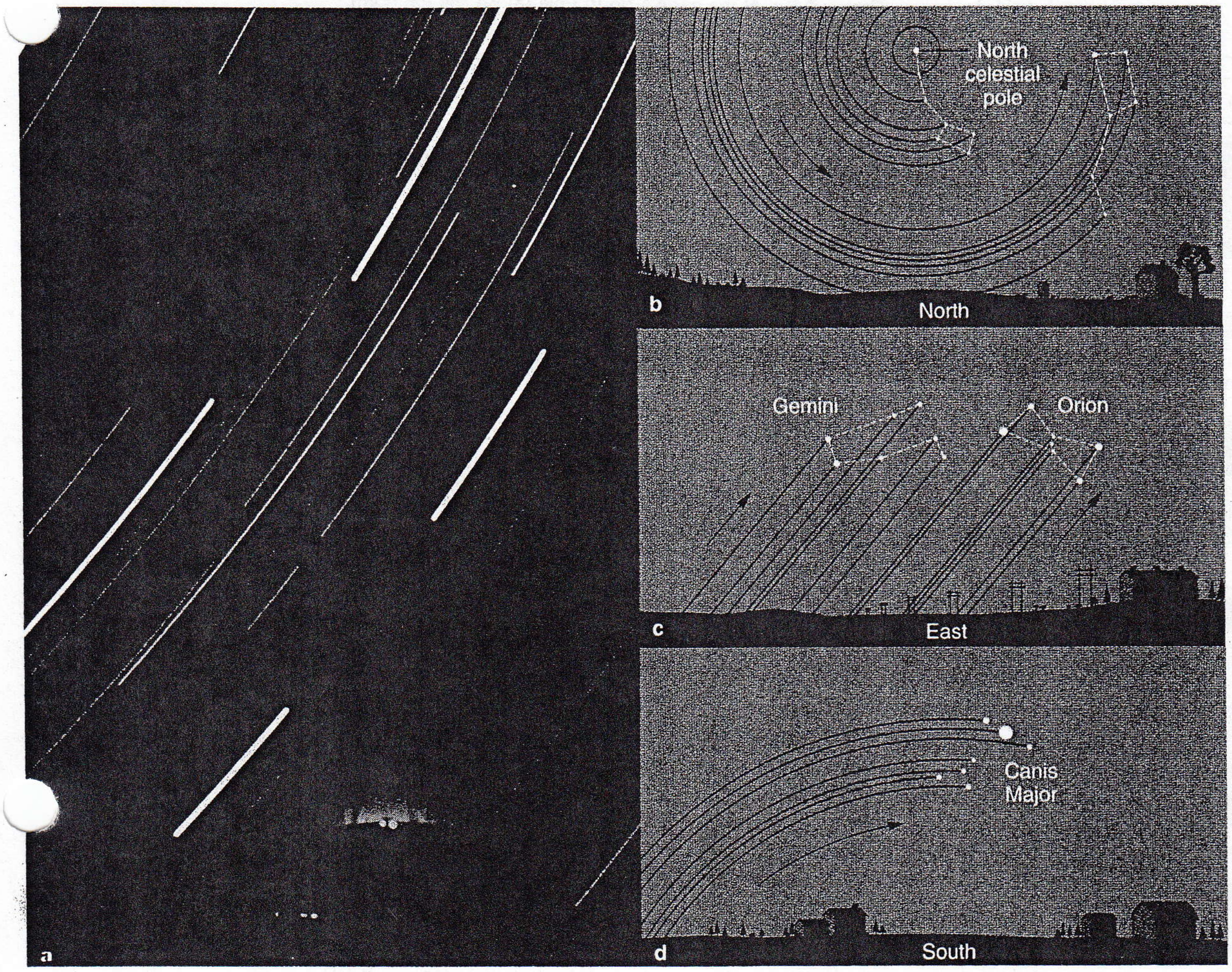


Figure 2-8 (a) A time exposure of a few hours shows stars as streaks due to the rotation of the earth. (National Optical Astronomy Observatory) (b) From the middle latitudes of the United States, about 40°N, we find the stars of the northern constellations circling the north celestial pole. (c) In the eastern sky, stars rise at an angle to the horizon. (d) In the south, the stars circle the south celestial pole, which is invisible below the southern horizon. Compare with Figure 2-7.

As the earth rotates eastward, the sky appears to rotate westward, and stars located near the celestial poles seem to follow small circles around the celestial poles (Figure 2-8b).

Another important reference mark on the sky is the **celestial equator,** an imaginary line around the sky directly above the earth's equator (Figure 2-7). Seen from mid-northern latitudes such as the United States, the celestial equator runs from the east point on the horizon up across the southern sky and down to the west point. Stars near the celestial equator rise along the eastern horizon parallel to the celestial equator (Figure 2-8c).

The location of the celestial poles and equator in our sky depends on our latitude. From any location on earth we can see half of the sky, the half above our horizon. Wherever we live, we feel "upright," and our horizon seems to be a horizontal circle around us dividing the sky into the half we can see and the half we cannot. Although

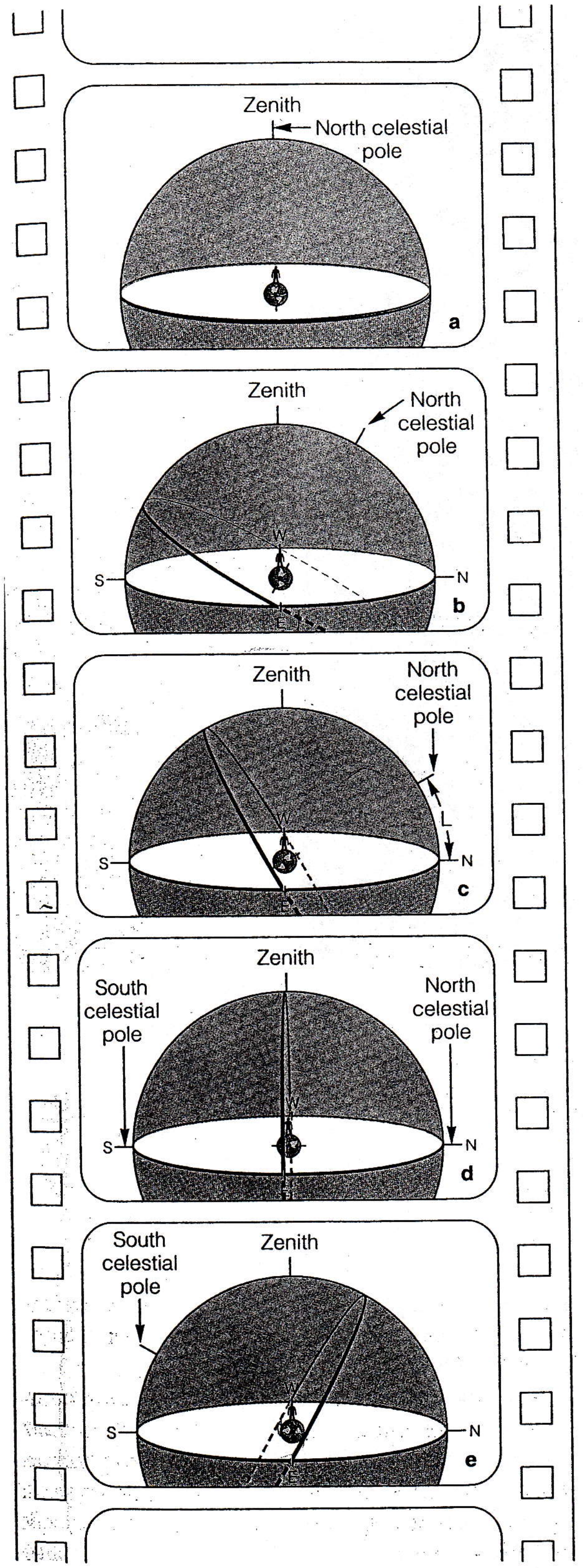


Figure 2-9 At the earth's North Pole (a) we see the north celestial pole directly overhead, and the celestial equator circles the horizon. As we journey southward (b) the angle between the north celestial pole and the northern horizon (L) always equals our latitude (c). At the earth's equator (d), we see the celestial poles on our horizon, and the celestial equator passes through our zenith. From southern latitudes (e) we see the south celestial pole above our horizon.

Australians and Alaskans feel that they are standing upright, they have very different horizons and see different portions of the sky.

To understand how our location affects the appearance of the sky, imagine a journey from the earth's North Pole to Argentina (Figure 2-9). We begin standing in the ice and snow around the North Pole, and the north celestial pole is directly overhead. The celestial equator runs along our horizon. As we begin walking southward from the pole, the north celestial pole begins to move away from the zenith into the northern sky, and the celestial equator rises above the southern horizon. As we walk southward, the angle between the north celestial pole and the northern horizon always equals our latitude (Figure 2-9c). This relationship makes it simple for navigators in the earth's Northern Hemisphere to find their latitude by measuring this angle.

On our journey southward we notice the celestial equator running from the east point on our horizon across the southern sky. As we cross the earth's equator, the celestial equator passes through our zenith, and the celestial poles lie on the northern and southern horizons (Figure 2-9d). Now as we walk farther southward, the north celestial pole sinks below our northern horizon, and the south celestial pole rises above our southern horizon.

From mid-northern latitudes we see the north celestial pole above our northern horizon. Currently the star Polaris happens to lie very near the north celestial pole, and thus it hardly moves as the sky rotates. (The Pawnee Indian name for this star means "Star That Does Not Walk Around.") Figure 2-10 shows how Polaris, the brightest image, hardly moves as the sky rotates about its axis. At any time of the night, in any season of the year, from anywhere in the earth's Northern Hemisphere, Polaris always stands above the northern horizon and is consequently known as the North Star. In the next section, we will see that other stars have occupied this location in the past.

Because it lies below our horizon, the south celestial pole is never visible from the United States. As seen from

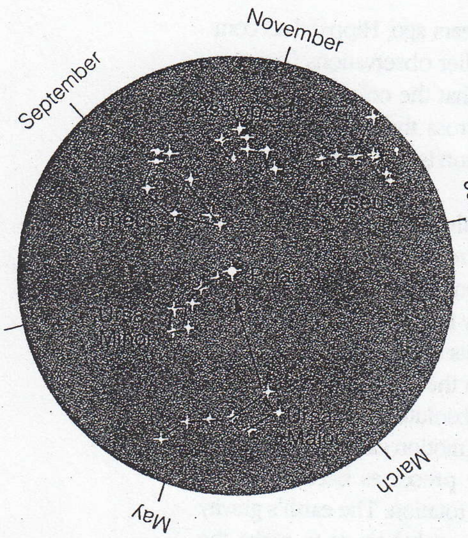
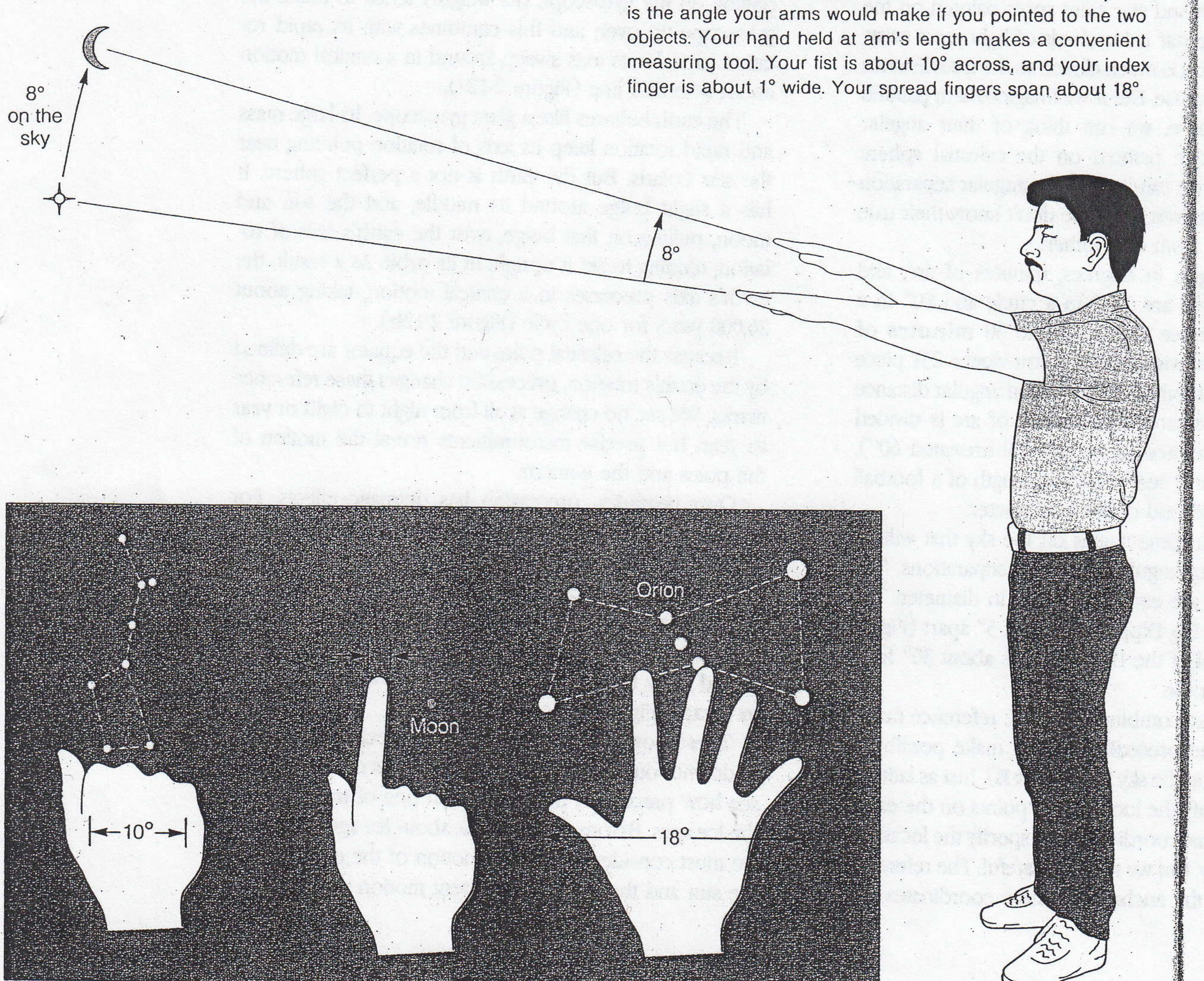


Figure 2-10 The northern constellations seen from mid-northern latitudes. To use the chart, face north soon after sunset and hold the chart in front of you with the current month at the top.

Figure 2-11 The angular separation between two objects is the angle your arms would make if you pointed to the two objects. Your hand held at arm's length makes a convenient measuring tool. Your fist is about 10° across, and your index finger is about 1° wide. Your spread fingers span about 18°.



our latitude, the constellations near the south celestial pole never rise, and the constellations near the north celestial pole never set. These constellations are known as **circumpolar constellations.** The farther north you live, the more circumpolar constellations you see. For most of us Ursa Major, containing the Big Dipper, is a north circumpolar constellation. In fact, we can always find the North Star by first finding the Big Dipper and then following the pointer stars in the dipper toward Polaris (Figure 2-10).

Angles on the Sky Astronomers often use angles to describe separations across the sky. They might say, for instance, that the moon is 8° north of a certain star, meaning that if we point one arm at the moon and the other arm at the star, the angle between our arms is 8° wide (Figure 2-11).

When astronomers speak of such angles, they use the phrase "angles on the sky" as if the sky were a great plaster ceiling and the moon and star were spots painted on the plaster. We know the star is hundreds of light-years away, and we know the moon is much closer, so the true distance between them is immense. But if we imagine them painted on the celestial sphere, we can think of their angular separation as an angle painted on the celestial sphere (Figure 2-11). Thus, we can discuss the angular separation between two objects even when we don't know their true distance from us or from each other.

We measure angles in degrees, minutes of arc, and seconds of arc. There are 360° in a circle and 90° in a right angle. Each degree is divided into 60 **minutes of arc** (sometimes abbreviated 60′). If you view a 25¢ piece from the length of a football field, it has an angular distance of about 1 minute of arc. Each minute of arc is divided into 60 **seconds of arc** (sometimes abbreviated 60″). The dot on this letter i seen from the length of a football field is about one second of arc in diameter.

We can establish some angles on the sky that will be helpful in estimating angular sizes and separations. The sun and the moon are each about 0.5° in diameter. The pointer stars of the Big Dipper are about 5° apart (Figure 2-11), and the bowl of the Big Dipper is about 30° from the north celestial pole.

Angles on the sky combined with the reference marks we discussed in the preceding section make possible a coordinate system on the sky (Appendix B). Just as latitude and longitude specify the locations of points on the earth, the system of celestial coordinates can specify the locations of points on the sky. But we must be careful. The reference marks on the sky, the anchors for these coordinates, are defined by the earth's rotation, and the earth is wobbling like a toy gyroscope.

Precession Two thousand years ago, Hipparchus compared his observations with earlier observations (presumably Babylonian) and realized that the celestial poles and equator were slowly moving across the sky. Later astronomers understood that this motion is caused by the toplike motion of the earth.

If you have ever played with a gyroscope, you have seen how the spinning mass resists any change in the direction of its axis of rotation. The more massive the gyroscope and the more rapidly it spins, the more difficult it is to change the direction of its axis of rotation. But you may recall that the axis of even the most rapidly spinning gyroscopes does not remain absolutely fixed. A spinning gyroscope wobbles in a conical motion called **precession** (Figure 2-12a). The gyroscope precesses because of the interaction of its weight and its rotation. The earth's gravity pulling on the gyroscope (its weight) tends to make the gyroscope tip over, and this combines with its rapid rotation to make its axis sweep around in a conical motion about a vertical line (Figure 2-12a).

The earth behaves like a giant gyroscope. Its large mass and rapid rotation keep its axis of rotation pointing near the star Polaris. But the earth is not a perfect sphere. It has a slight bulge around its middle, and the sun and moon, pulling on that bulge, twist the earth's axis of rotation, tending to set it upright in its orbit. As a result, the earth's axis precesses in a conical motion, taking about 26,000 years for one cycle (Figure 2-12b).

Because the celestial poles and the equator are defined by the earth's rotation, precession changes these reference marks. We see no change at all from night to night or year to year, but precise measurements reveal the motion of the poles and the equator.

Over centuries, precession has dramatic effects. For example, it makes the celestial poles move across the sky. Egyptian records show that 4800 years ago, the north celestial pole was near the star Thuban (α Draconis). The pole is now approaching Polaris and will be closest to it about AD 2100. In about 12,000 years the pole will have moved away from Polaris and will be within 5° of Vega (α Lyrae) (Figure 2-12c).

These slow changes in the sky may seem to have little to do with our lives, but at the end of this chapter we will see how precession may have been one of the causes of the ice ages. Before we can think about ice ages, however, we must consider the orbital motion of the earth around the sun and the resulting apparent motion of the sun.